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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 29-12-2008		2. REPORT TYPE Final Performance Technical Report		3. DATES COVERED (From - To) 21 February 2005-30 September 2008	
4. TITLE AND SUBTITLE Mixed Layer Model Testing in Complex Environments				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-05-1-0330	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Ramsey Harcourt				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory, University of Washington 1013 N.E. 40th Street Seattle, WA 98105				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Scott Harper Office of Naval Research, Code 322 875 North Randolph Street Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT UU					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The PI attended three ONR workshops to present and discuss results within the DRI on Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP) and presented results at the 2007 Ocean Sciences AGU meeting. The results are discussed in this final report.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES  4	19a. NAME OF RESPONSIBLE PERSON Ramsey Harcourt
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER (include area code) 206-221-4662

## Final Technical Report

ONR Grant # N00014-05-1-0330

Performance Period: 21 February 2005 – 31 September 2008

Total Award: \$223,691

### Mixed Layer Model Testing in Complex Environments

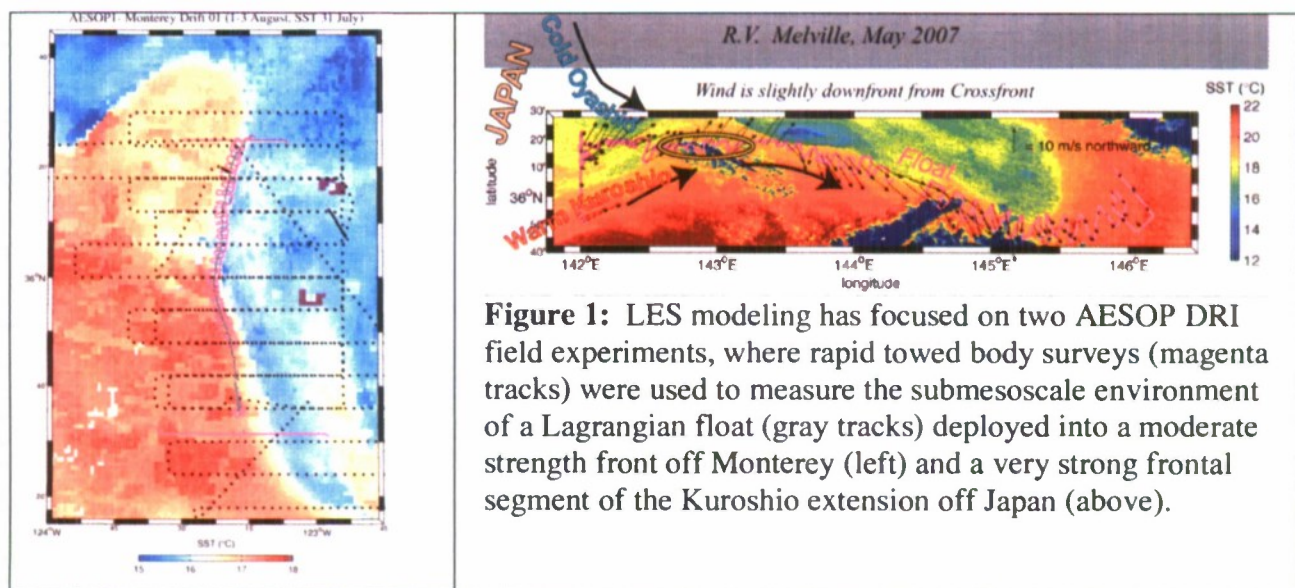
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The PI attended three ONR workshops to present and discuss results within the DRI on Assessing the Effects of Submesoscale Ocean Parameterizations (AESOP), and presented results at the 2007 Ocean Sciences AGU meeting. Results and interactions with other DRI scientists have focused on the physics underlying lateral fluxes at submesoscales in the upper ocean due to horizontal mixing processes that are below the  $O(1) - O(10)$  km horizontal resolution scale of regional ocean models. Modeling work as part of the AESOP DRI has studied surface boundary layer horizontal mixing processes in regions of significant horizontal variability, as commonly found in frontal regions. Focus on the upper ocean boundary layer has sought to quantify the coupling between mixed layer vertical fluxes and the dynamics of lateral mixing by submesoscale coherent structures.

A crucial element of this numerical research has been the resolution of 3D large-eddy turbulence in boundary layers of depths  $10\text{m} < H_{ML} < 100\text{m}$ . This  $O(1-10)$  m isotropic resolution has enabled model-data comparisons against measurements of turbulence and dispersion that may thereby critically assess the role of mixed layer dynamics and surface-driven vertical mixing in the cascades of baroclinic potential energy into submesoscale lateral mixing processes. Within the AESOP DRI, Large Eddy Simulations (LES) have been done in close collaboration with field experiments measuring upper-ocean mixing processes in the strong lateral density gradients of the Kuroshio and in a weaker front off Monterey, during periods of varying wind and wave forcing (Fig. 1).

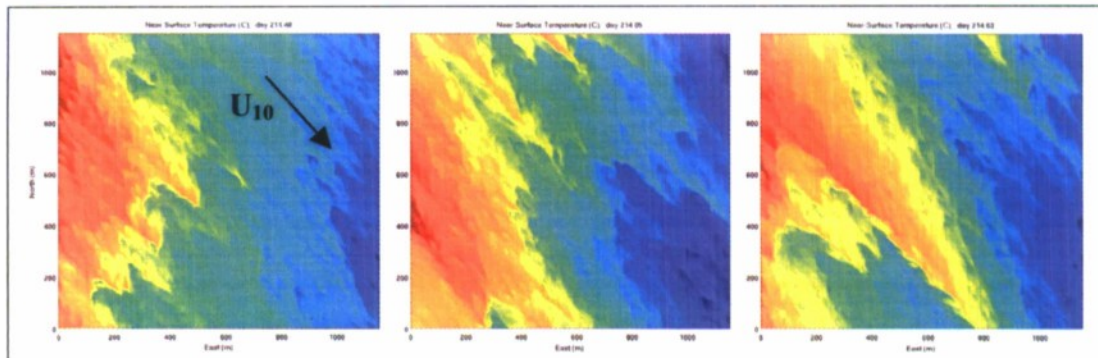


**Figure 1:** LES modeling has focused on two AESOP DRI field experiments, where rapid towed body surveys (magenta tracks) were used to measure the submesoscale environment of a Lagrangian float (gray tracks) deployed into a moderate strength front off Monterey (left) and a very strong frontal segment of the Kuroshio extension off Japan (above).



LES modeling of mixed layer turbulence in these field conditions imposed the profile of horizontal stratification within the front as uniform background forcing in otherwise periodic realizations of the dynamics at  $O(1)$  to  $O(10^3)$  m length scales (Fig. 2). This column model approach limits realization of larger scale frontal features, but does include principal local scalar gradient components that submesoscale turbulence closure of dynamics at  $<O(1)$  km would require (c.f. the parameterization of Fox-Kemper et al., 2007). Surface forcing combined ship-based meteorological observations with surface wave spectra simulated using Wave Watch III (courtesy of NRL Monterey & FNMOC). Results from AESOP simulations of upper-ocean mixing in the Monterey front (Fig. 2) include:

- Rapid deepening occurs during downfront wind events due to ‘Ekman adjustment’ as cross-front lateral advection against reduces pycnocline stability.
- Vertical turbulent kinetic energy (VKE) was unaffected by baroclinicity in both the observations and the LES of the weaker Monterey front, and consistent with Langmuir turbulence scaling (D’Asaro, 2001, Harcourt and D’Asaro, 2008).
- Horizontal scalar fluxes by 100-600m structures (Fig. 2) develop rapidly as surface-driven vertical mixing generates ageostrophic currents.
- Submesoscale lateral flux magnitudes are similar to lateral dispersion by mean vertical shear and stratification; restratification processes are also enhanced.
- Lateral fluxes are skew-directional with magnitudes that depend on the strength of vertical mixing, as well as horizontal stratification, Coriolis, and layer depth.
- The down- and cross-gradient fluxes can be scaled together with horizontal kinetic energy.



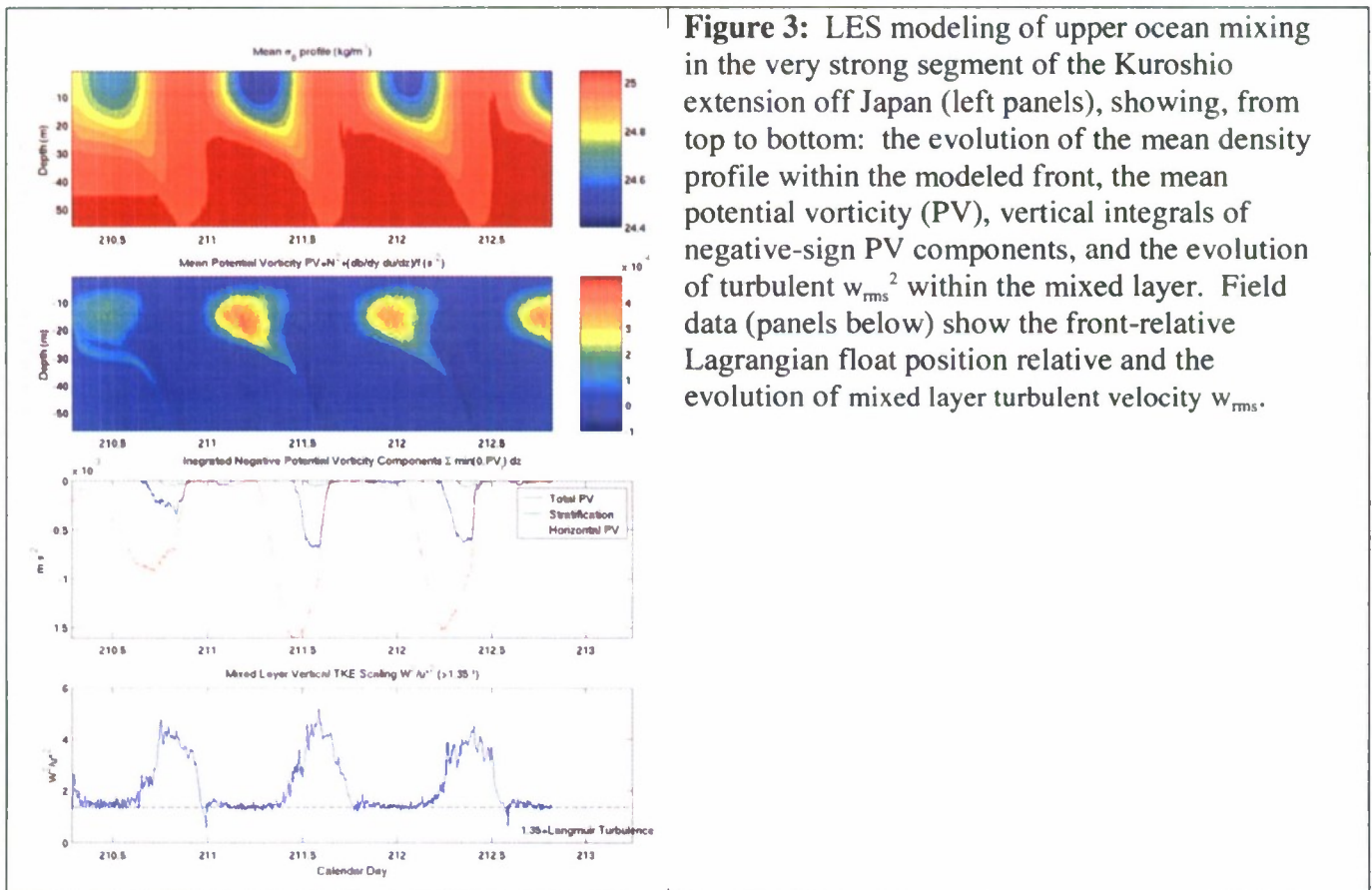
**Fig. 2:** LES sea surface temperature evolution over 28 hours in the Monterey front with E-W density gradient  $0.0625 \text{ kg/m}^3/\text{km}$ , while forced by wind stress and surface waves. Large horizontal turbulent fluxes are carried by the 100-600m scale structures at 2-10 times the mixed layer depth. These submesoscale features grow to 3-20 times mixed layer depth and the Langmuir jet spacing (still visible at  $O(10)\text{m}$  fine scales). They develop rapidly after surface forcing increases and are oriented by the surface wind stress and waves.

One advantage of the 1-D representation of the front by the profile of lateral density gradients is that such LES results can provide controlled tests of mixed layer parameterizations, and this has been done for the K-Profile Parameterization (KPP) of Large et al (1994). This intercomparison shows KPP to deepen too much when turbulence-independent Ekman adjustment dominates LES deepening. More critically, the use of KPP in lieu of resolving mixed-layer Langmuir turbulence with surface-wave forcing results in a significant difference in the profile of Potential Vorticity (PV). This illustrates the

trade-offs between resolving 3D turbulence in a limited domain size and resolving the largest submesoscale features with parameterized mixed layer dynamics.

In applying this local gradient far-field forcing approach to the stronger front case of the Kuroshio extension, a depth-varying profile of lateral density and spice gradient is imposed, corresponding in scale to that observed across this rapidly spreading front. Surface stress and Stokes drift forcing is based on a typical observed, largely cross-front wind with  $u^* = 1.2$  cm/s and fully developed downwind seas. This constant-forcing LES case (Fig 3) produced strong variations in lower mixed layer stratification on inertial periods, the growth of which is limited by shear instabilities in the mixed layer base.

The maxima in both observed and modeled mixed layer VKE  $w_{rms}^2$  represent a clear departure from Langmuir turbulence scaling ( $w_{rms}^2 \sim 1.35 u^{*2}$ ), and coincide in the model with maxima in total negative PV. The observed duration, magnitude and uniqueness of this mixed layer turbulence production in the O(1) day observation record are consistent with the inertially periodic simulated instability. However, the growth of the instability precedes the appearance of mean negative PV on the  $144 \times 144$  m<sup>2</sup> horizontal domain scale, indicating that the conversion of baroclinic energy to 3D turbulence begins when mean PV grows negative on a smaller lateral scale. While it is somewhat surprising to find this agreement between the observations and a model with only 1<sup>st</sup> order ingredient representation of the density field, this result is nonetheless consistent with the understanding that symmetric or centrifugal instabilities are unstable inertial oscillations that drain baroclinic potential energy into diapycnal mixing events.





Modeling results for the moderate California Current case and the strong Kuroshio extension case are profoundly different. The growth of submesoscale features in the large domain Monterey front (Fig. 2) represents an *inverse* cascade of energy from instabilities of the front brought on by a departure from geostrophic balance by 'finescale' mixed layer turbulence. On the other hand, the phenomenon encountered in the Kuroshio extension (Fig. 3) represents *forward* cascade of energy from frontogenetic mesoscale straining through submesoscale instabilities and down into turbulent vertical and lateral mixing.

**One very remarkable feature that both Monterey and Kuroshio simulations do share is that the modeled instabilities and mixing intensities depend strongly on surface forcing.** Simulations of the Monterey front without the additional forcing from surface wave Stokes drift yield lateral fluxes that are reduced, in proportion to the reduction from Langmuir turbulence VKE scaling to wave-free boundary layer levels ( $w_{rms}^2 \sim 0.64u_*^2$ ). In the Kuroshio extension case, removing the surface wind and wave forcing produces similar inertial oscillations that do not become unstable and do not produce such bursts of TKE through shear instabilities. The lateral fluxes examined in the Monterey case are also present and stronger in the Kuroshio case, but the dependence on permitted scales (i.e. LES domain size) is not yet determined. What is particularly interesting though is that the shear instability responsible for periodically elevating VKE simultaneously shuts down the lateral mixing by submesoscale fluctuations.

While the local gradient LES formulation limits the upper range of resolved dynamic scales, it preserves the resolution of mixed layer large-eddies critical to validity of the subgrid closure. This validity is essential to being able to clearly identify forward cascades of energy to the mixed layer 3D turbulence scales on the basis of observed and modeled VKE levels. The comparisons with Lagrangian float turbulence measurements have been surprisingly good, particularly in new results from the stronger-front Kuroshio case. Note that we are also able to make a clear identification of the departure in VKE scaling from Langmuir turbulence because we have a robust basis for predicting it in the absence of fronts and a statistically significant observed departure from that prediction.

In addition to the numerical modeling work, and participation in DRI workshops, the PI participated in the both field experiments as the 'man on the beach', providing the science parties with satellite and regional model products. In the context of the Monterey experiments, the PI facilitated the flow of ocean data from the AESOP field program to the participants in the co-located ASAP MURI, leading to improvements in at least the HOPS model participants there. In the context of the field experiments in the Kuroshio current, the satellite products provided by the PI led the field program eventually to the very interesting results that have been obtained in this very strong frontal system. Above all, this participation with the field program has been instrumental in designing greater realism into the numerical simulations.